Water Cherenkov Detector and Neutrino Oscillation Experiments Using $\nu_\mu \longrightarrow \nu_e$ (Update)

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FNAL/BNL Joint Study on Long Baseline Neutrino at Fermilab

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• Very Long Baseline Neutrino Oscillation Experiment

- Setting the stage
  - ~ a half megaton F.V. water Cherenkov detector, for example UNO at 2,540 (BNL-HS) km and 1,480 km (Fermilab-Henderson) from the beam source
  - BNL very long baseline wide band neutrino beam
  - VLB neutrino oscillation experiment $\nu_\mu \to \nu_e$

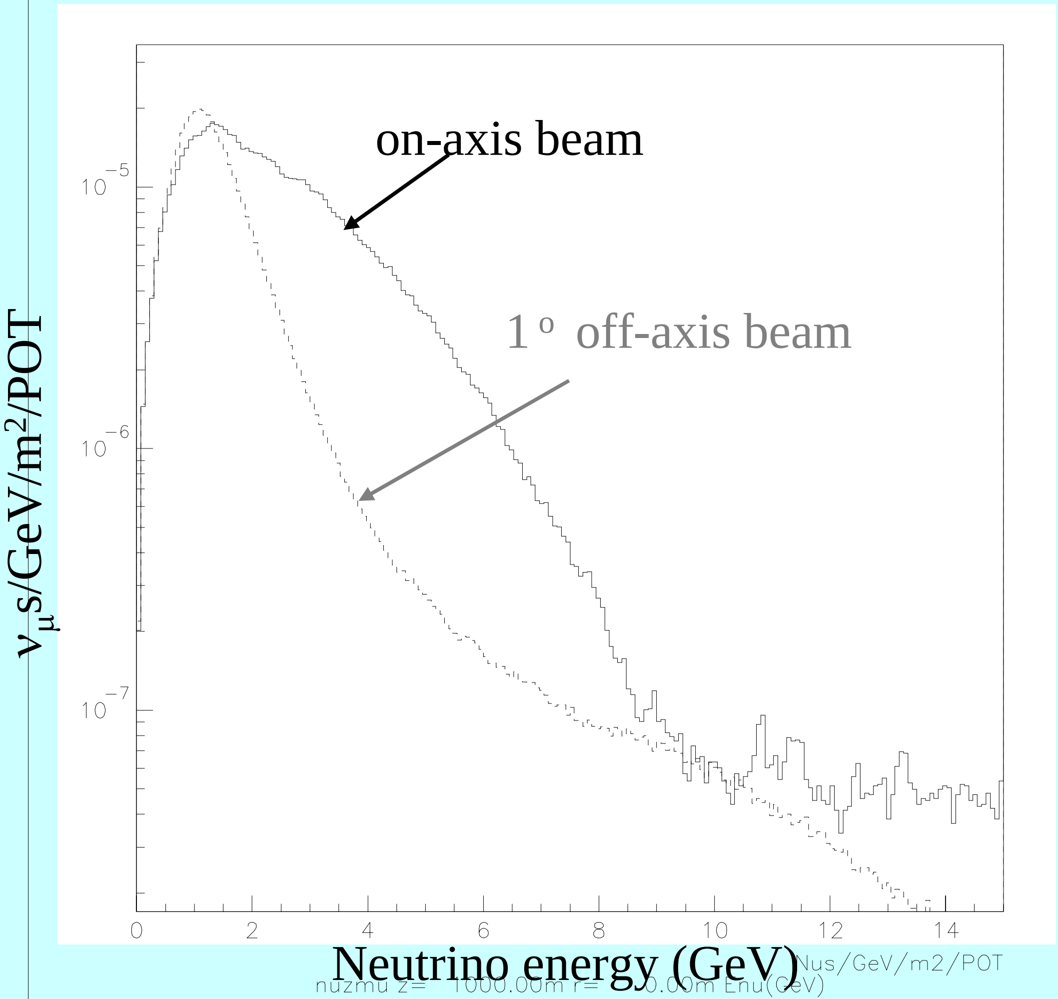
  See, for example, PRD68 (2003) 12002 by BNL group for physics argument.

  But it is based on 4-vector level MC and on very optimistic assumptions

- How do we find the signal for $\nu_\mu \to \nu_e$
  - $\nu_\mu \to \nu_e$ and $\nu_e + N \to e$ + invisible N' + (invisible n $\pi^\pm$s, n≥0)
  - Look for single electron events
  - Major background
    - $\nu_{\mu,\tau,e} + N \to \nu_{\mu,\tau,e} + N' + \pi^0$ + (invisible n $\pi^\pm$s, n≥0), $\pi^0 \to \gamma\ (\gamma)$
    - ν_e contamination in beam (typically 0.7%)

- Neutrino spectra of on- and off-axis BNL Superbeams

PRD68 (2003) 12002; private communication w/ M.Diwan



How is analysis done ?

- Use of SK atmospheric neutrino MC
  - Standard SK analysis package + special π^0 finder
  - Flatten SK atm. ν spectra and reweight with BNL beam spectra
  - Normalize with QE events: 12,000 events for ν_μ , 84 events for beam ν_e for 0.5 Mt F.V. with 5 years of running, 2,540 (1,480) km baseline

2500 kt• MW•10^7 sec
BNL 30 GeV AGS

distance from BNL to Homestake
(distance from Fermilab to Henderson)

  - Reweight with oscillation probabilities for ν_μ and for ν_e

- Oscillation parameters used:
  - **Δm^2_{21} =7.3 x 10^{-5} eV^2, Δm^2_{31}=2.5 x 10^{-3}eV^2**
  - **$\sin^2 2\theta_{ij}$(12,23,13)=0.86/1.0/0.04, δ_{CP}=0,+45,+135,-45,-135^o**

Probability tables from Brett Viren of BNL

• π^0 finder : Motivation and strategy

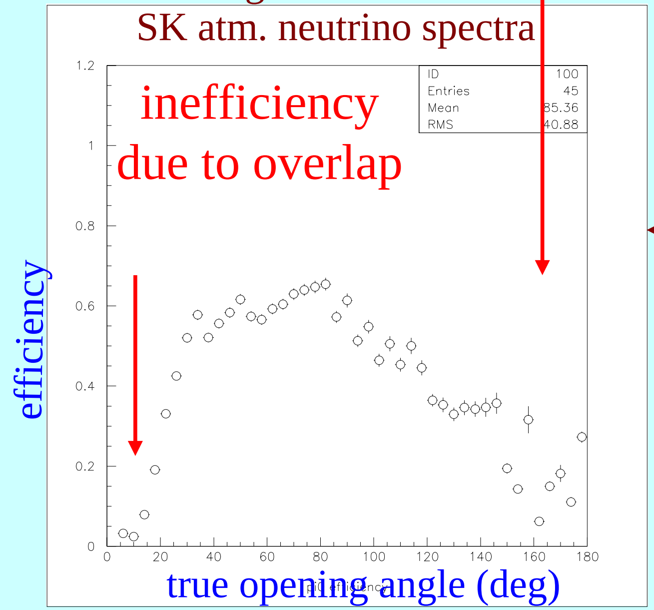
- π^0 reconstruction efficiency with standard SK software
  - Inefficiency due to overlap
  - Inefficiency due to a week 2^{nd} ring
  - Inefficiency in between

Needs a smart algorithm to increase efficiency

- POLfit (Pattern Of Light fit)
  - Always looks for an extra ring in a single e-like ring event
  - Compares observed light pattern with templates
  - Includes scattered light due to processes such as Mie scattering
  - Gives outputs such as likelihoods in addition to information of the extra-photon are provided

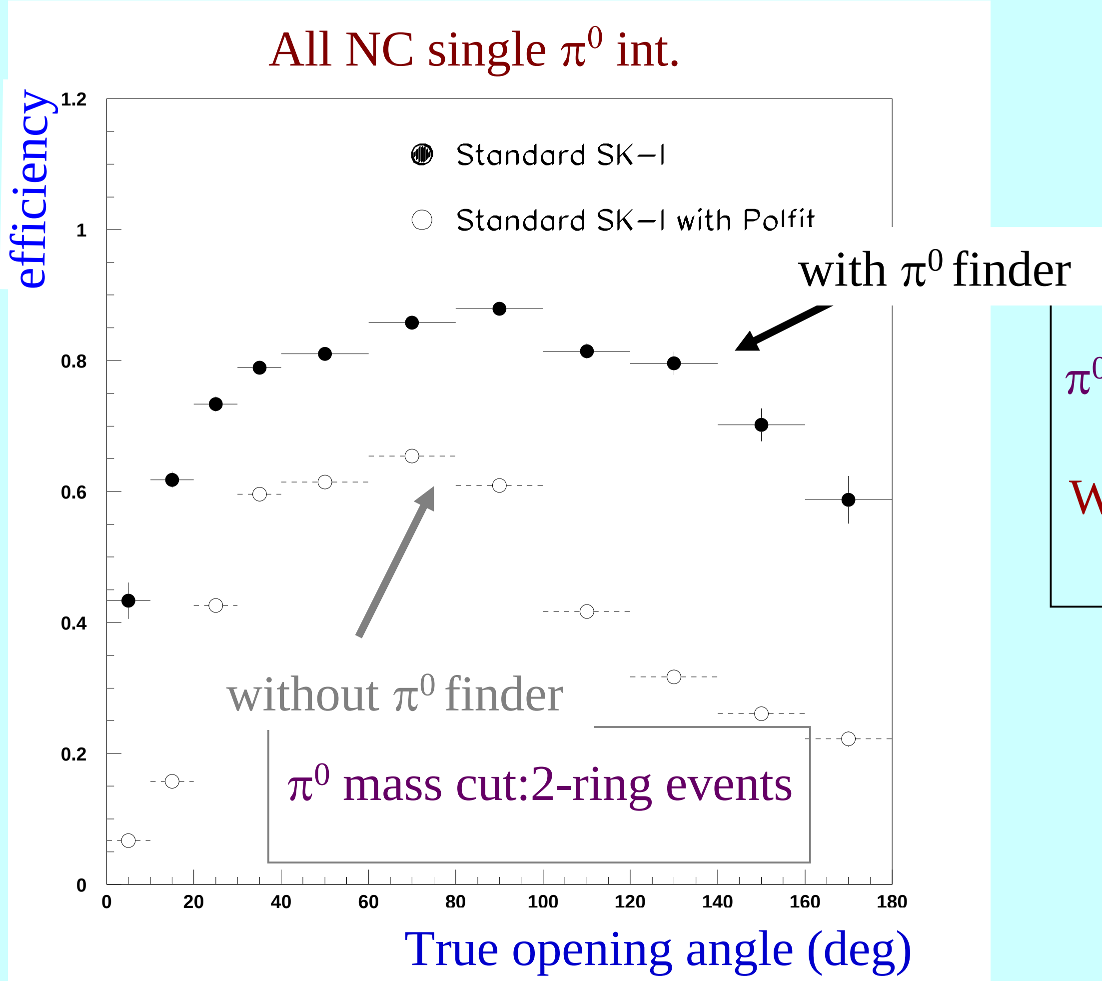
inefficiency due to weak 2^{nd} ring

All single π^0 interactions
SK atm. neutrino spectra



π⁰ finder: "Efficiency"

- π^0 "reconstruction efficiency" with standard SK + π^0 finder



with π^0 finder

w/o π^0 finder

π^0 mass cut:1- and 2-ring events

With atmospheric neutrino spectra

Selection criteria

- Initial cuts: Traditional SK cuts only
  - One and only one electron-like ring with energy and reconstructed neutrino energy more than 100 MeV without any decay electron

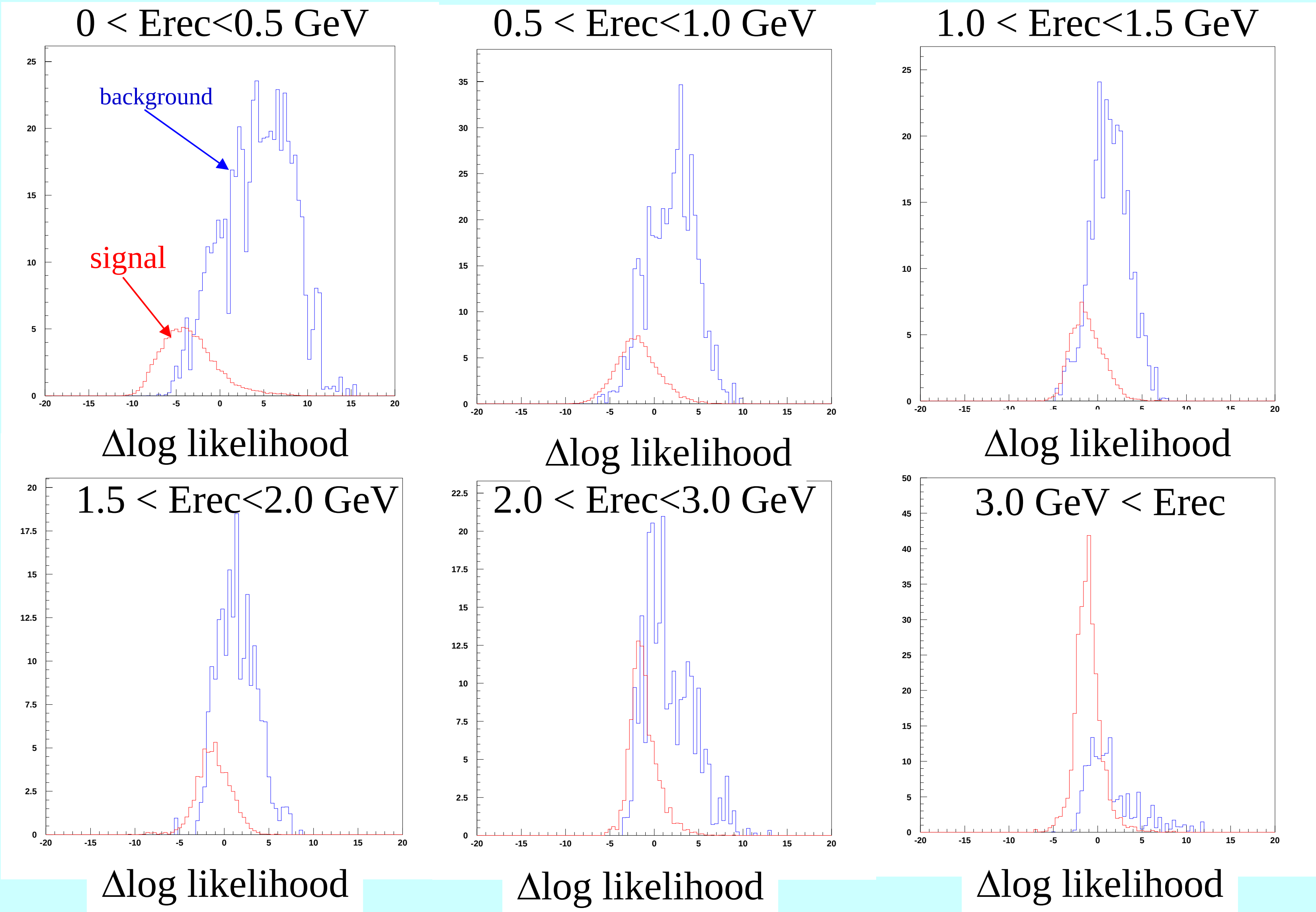
$$E_\nu^{rec} = \frac{m_N E_e}{m_N - (1-\cos\theta_e)E_e}$$

To reduce events with invisible charged pions

- Likelihood analysis using the following 9 variables: With π^0 finder
  - π^0 mass (pi0mass)
  - energy fraction (efrac)
  - $\cos\theta_{\nu e}$
  - π^0-likelihood (pi0-like)
  - e-likelihood (e-like)
  - $\Delta \log \pi^0$-likelihood (Δlog pi0like)
  - single ring-ness (dlfct)
  - total charge/primary ring energy (poa)
  - Cherenkov angle (ange)

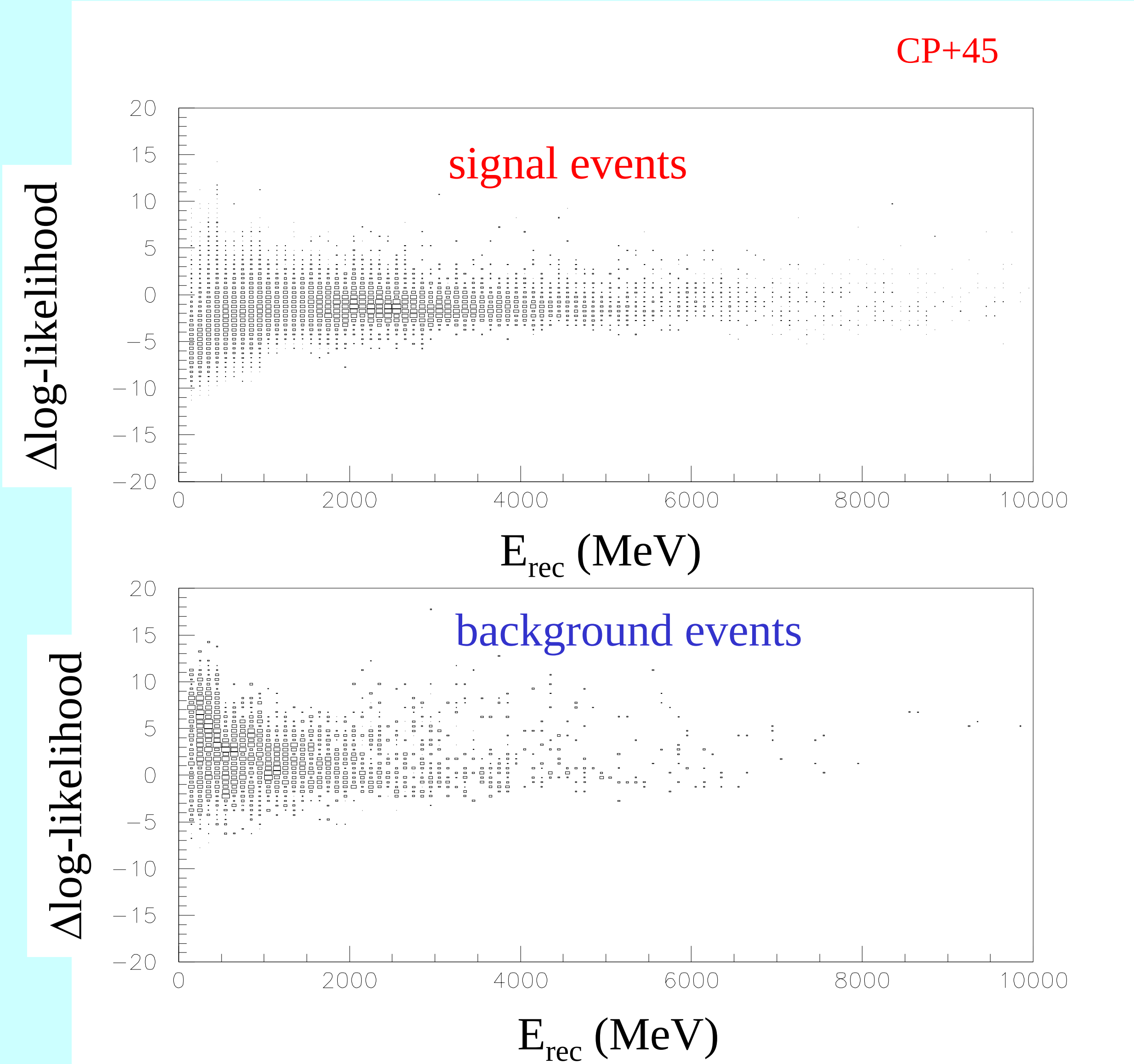
Trained with ν_e CC events for signal, ν_μ CC/NC & $\nu_{e,\tau}$ NC for bkg

- Δ log likelihood distributions log likelihood-ratio (signal vs. background)



Trained with ν_e CC events for signal, ν_μ CC/NC & $\nu_{e,\tau}$ NC for bkg

- Δ log-likelihood distributions log likelihood-ratio (signal vs. background)

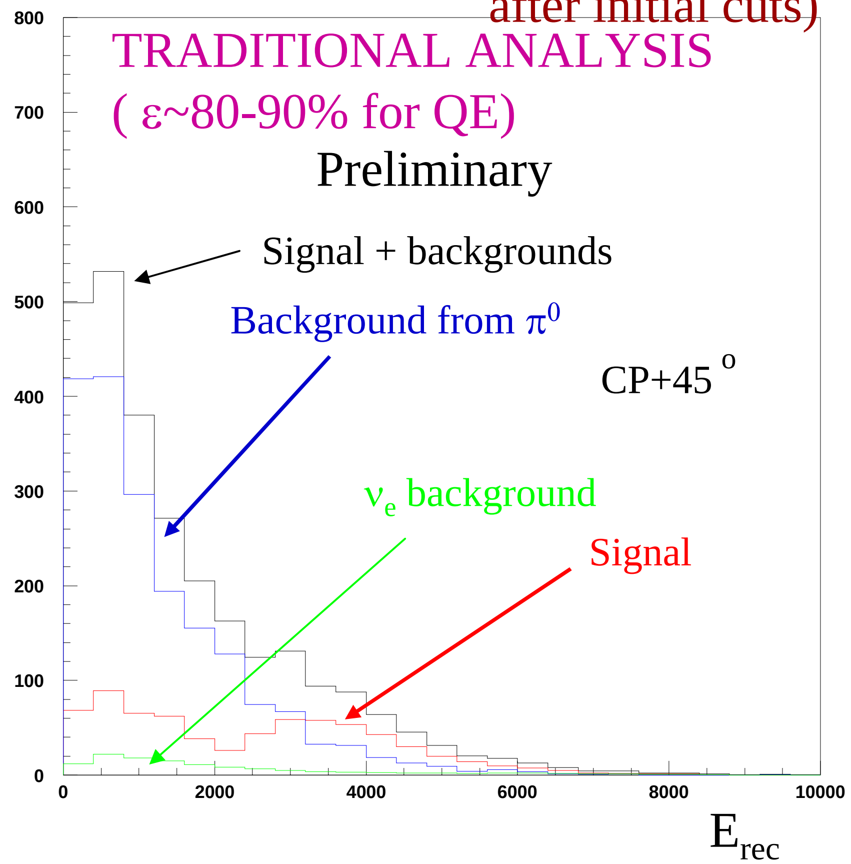


BNL-Homestake (2540 km)

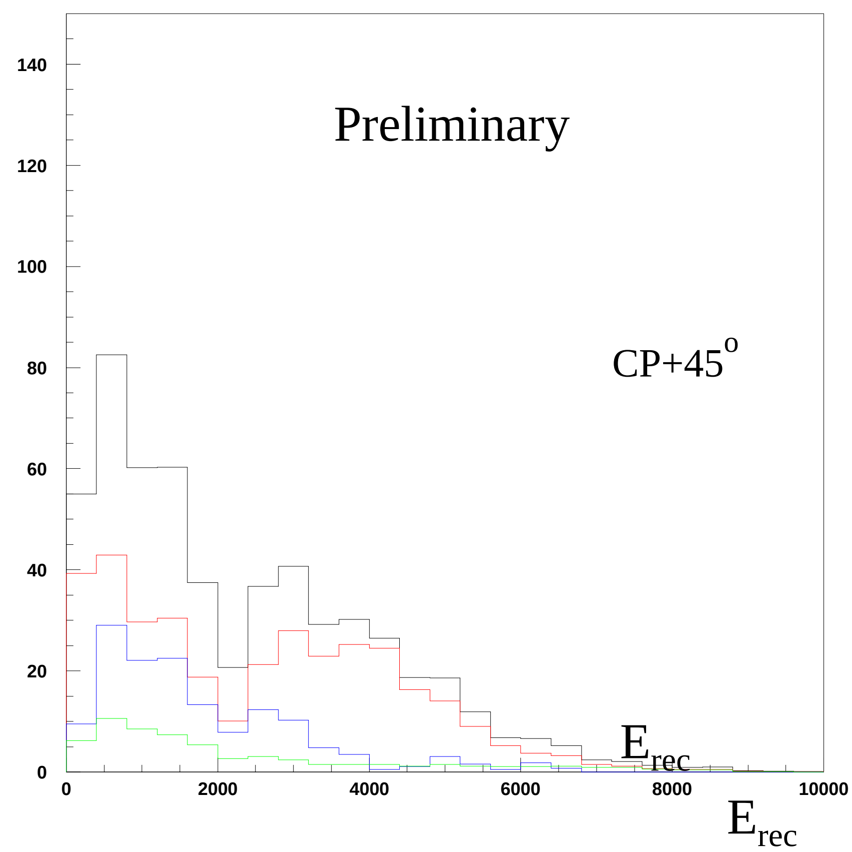
- Effect of cut on Δ log likelihood ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for background

After initial cuts

No Δ log-likelihood cut (100% signal retained after initial cuts)



Δ log-likelihood cut (~50% signal retained)



Signal 700 ev Bkgs 2004
(1877 from π^0+others)
(127 from ν_e)

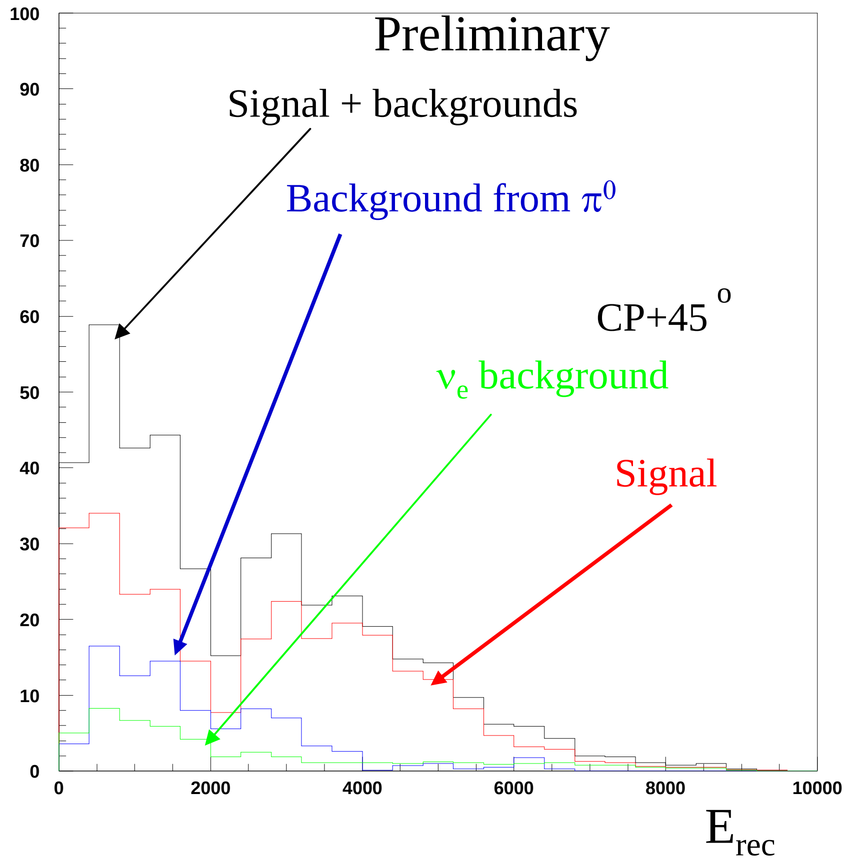
Signal 350 ev Bkgs 169
(147 from π^0+others)
(61 from ν_e)

BNL-Homestake (2540 km)

- Effect of cut on Δ log likelihood

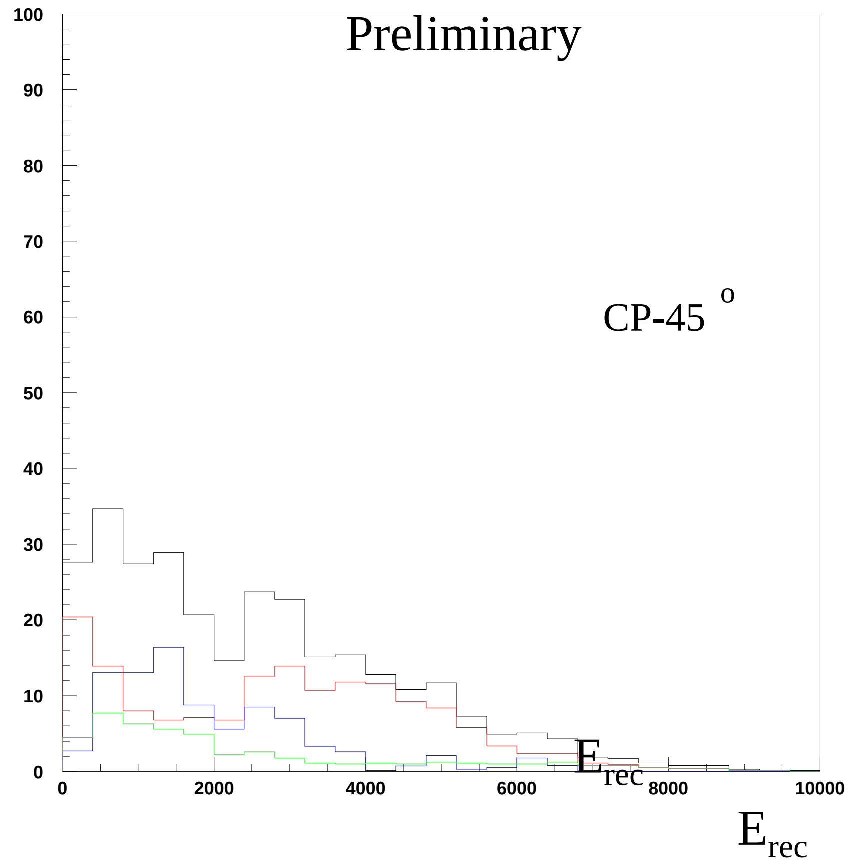
ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

Δ log likelihood cut (40% signal retained)



Signal 280 ev Bkgs 136
(87 from π^0+others)
(49 from ν_e)

Δ log likelihood cut (~40% signal retained)



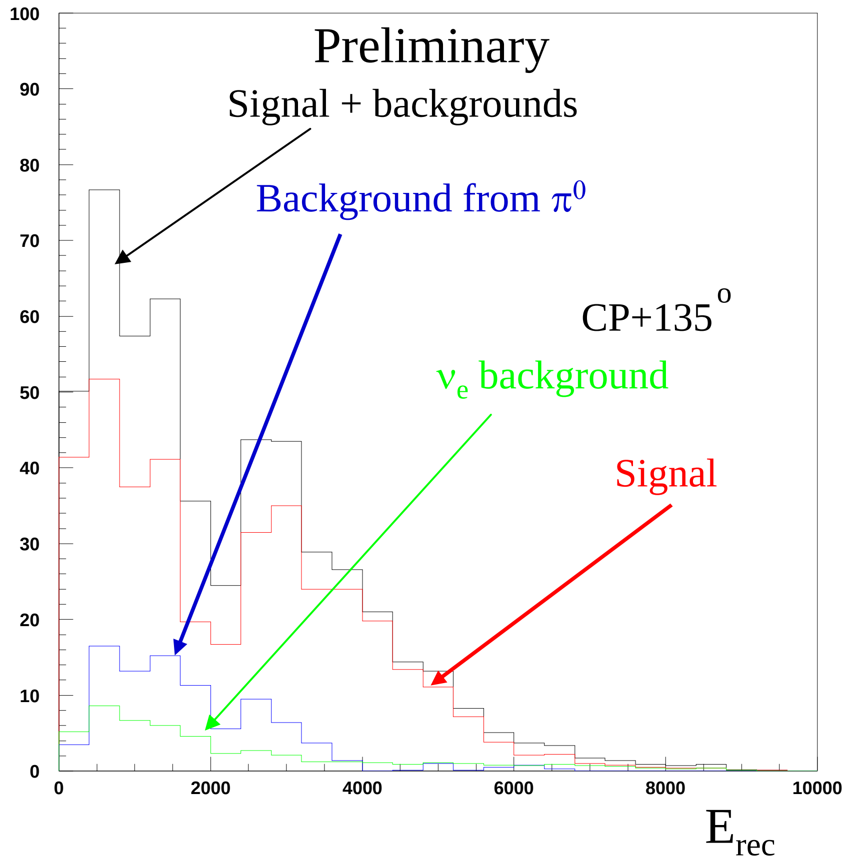
Signal 158 ev Bkgs 135
(87 from π^0+others)
(48 from ν_e)

BNL-Homestake (2540 km)

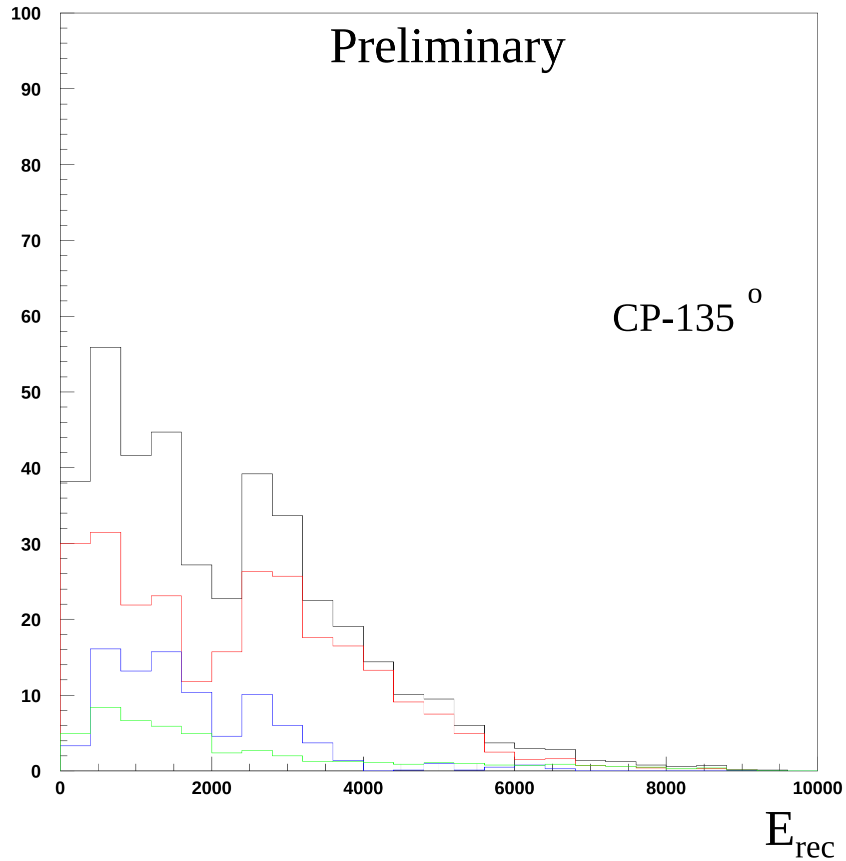
- Effect of cut on Δ log-likelihood

ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

Δ log-likelihood cut (40% signal retained)



Δ log-likelihood cut (~40% signal retained)



Signal 386 ev Bkgs 136
(89 from π^0+others)
(50 from ν_e)

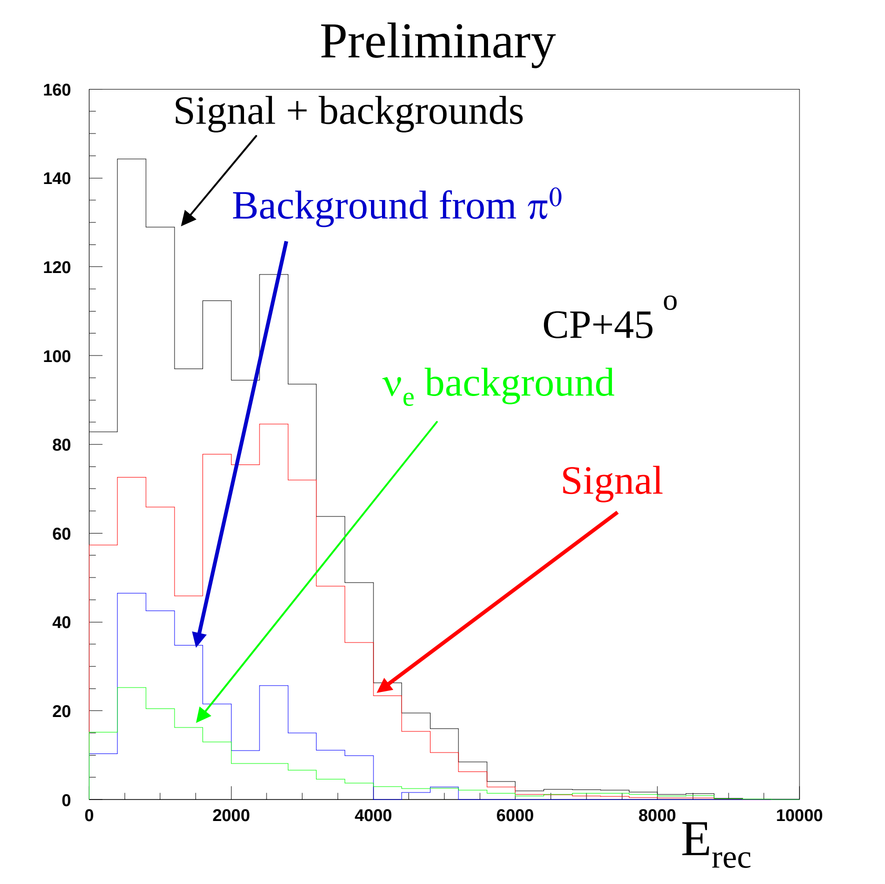
Signal 263 ev Bkgs 136
(87 from π^0+others)
(49 from ν_e)

Fermilab-Henderson (1480 km)

- Effect of cut on Δ log-likelihood

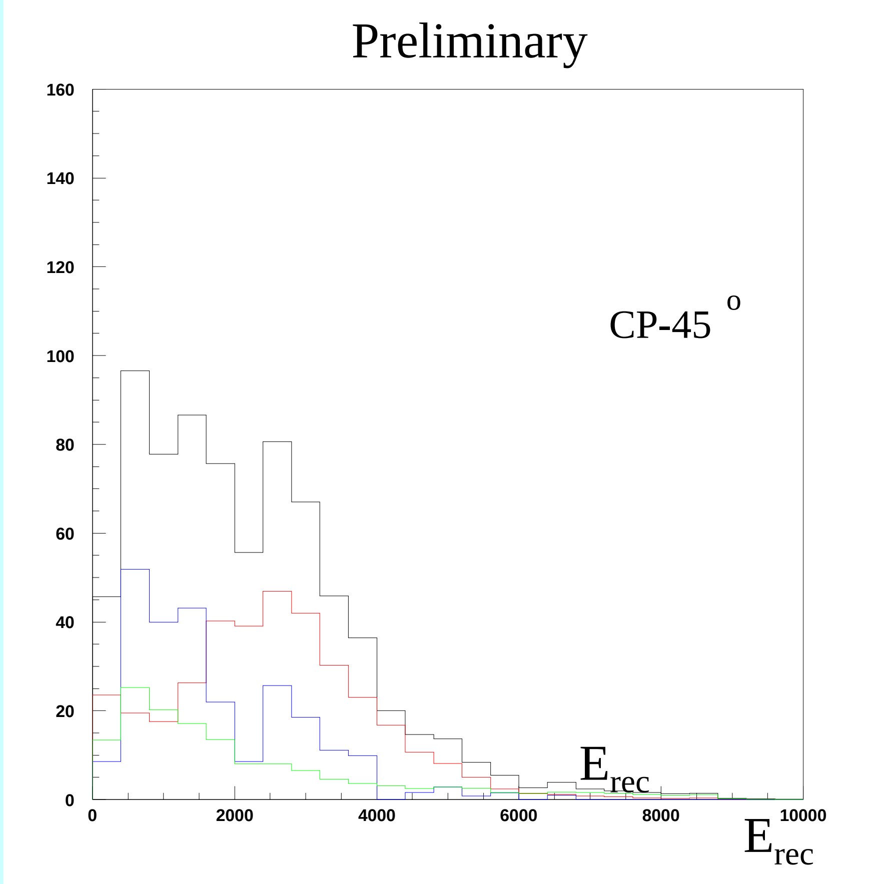
ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

Δ log-likelihood cut (40% signal retained)



Signal 699 ev   Bkgs 373
(233 from π^0+others)
(141 from ν_e)

Δ log-likelihood cut (~40% signal retained)



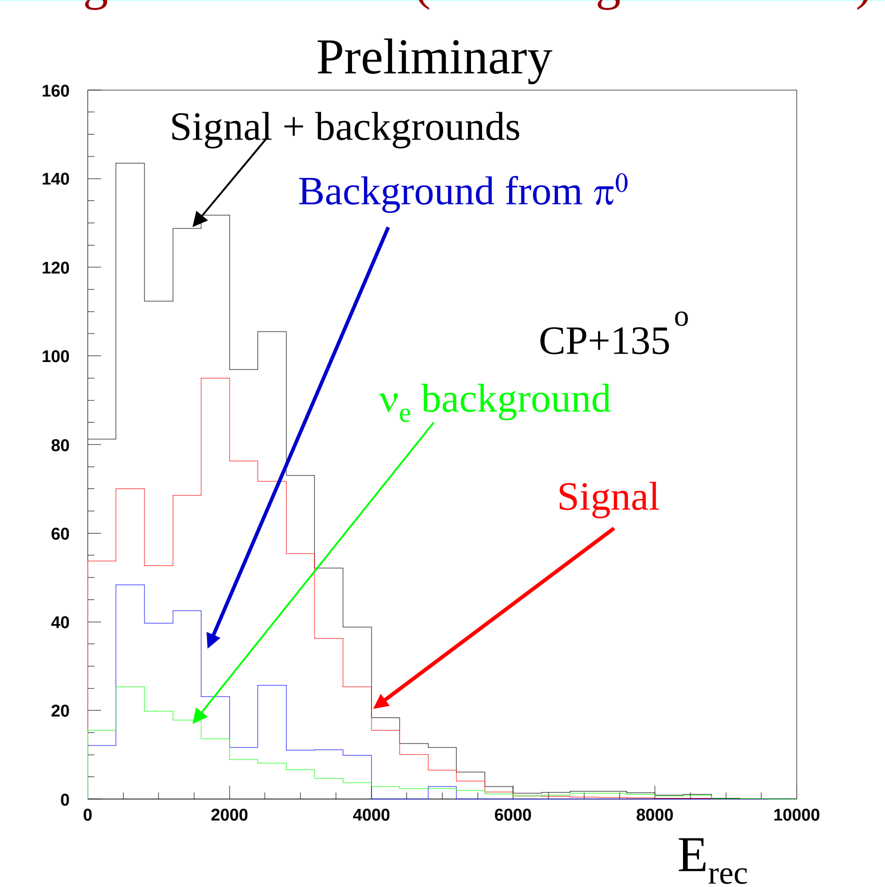
Signal 357 ev   Bkgs 389
(247 from π^0+others)
(142 from ν_e)

Fermilab-Henderson (1480 km)

- Effect of cut on Δ ln likelihood

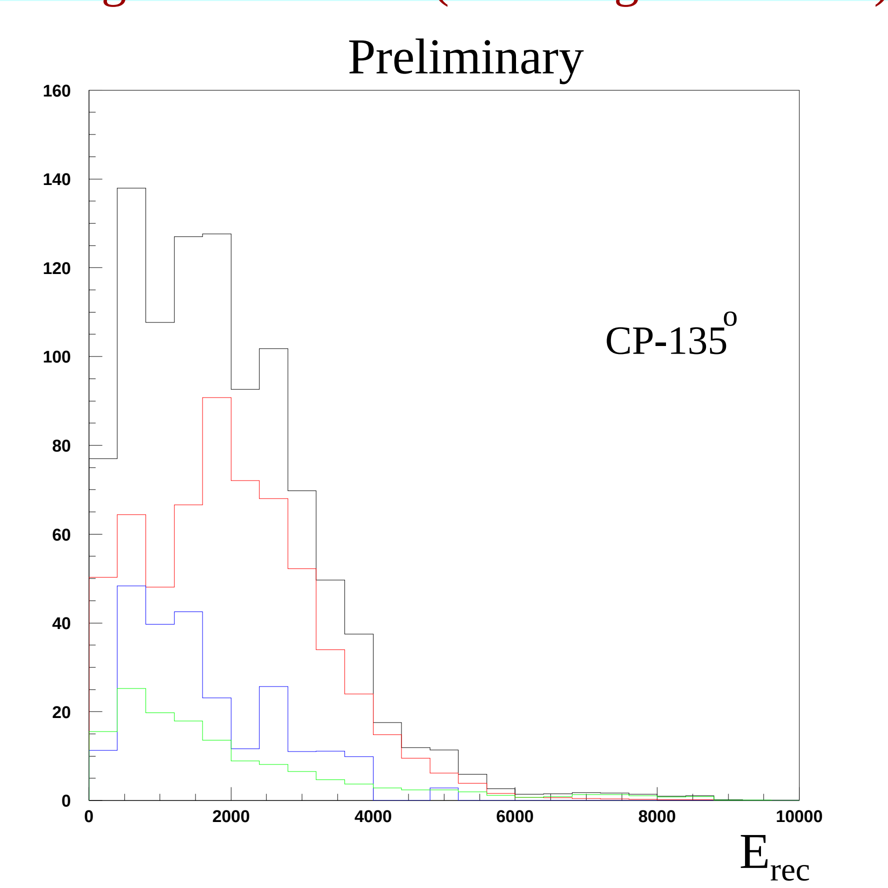
ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for backgrounds

Δ log-likelihood cut (~40% signal retained)



Signal 645 ev Bkgs 379
(237 from π^0+others)
(142 from ν_e)

Δ log-likelihood cut (~40% signal retained)



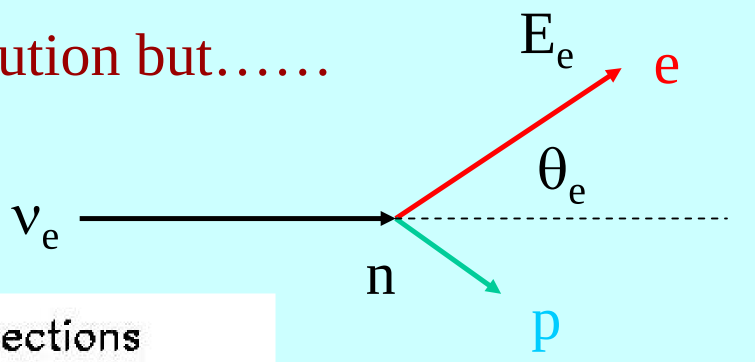
Signal 609 ev Bkgs 379
(237 from π^0+others)
(142 from ν_e)

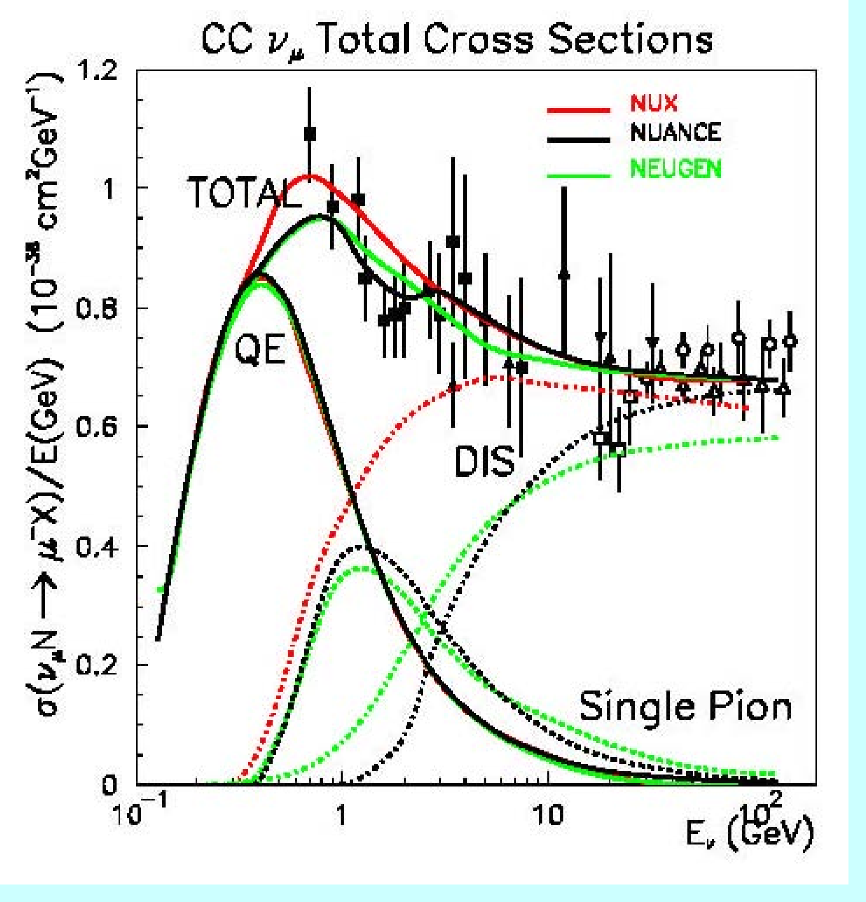
- How good is the neutrino energy measurement?

  - **Neutrino energy reconstruction**

QE events give the best energy resolution but……

$$E_\nu^{rec} = \frac{m_N E_e}{m_N - (1-\cos\theta_e)E_e}$$





BNL-Homestake (2540 km)

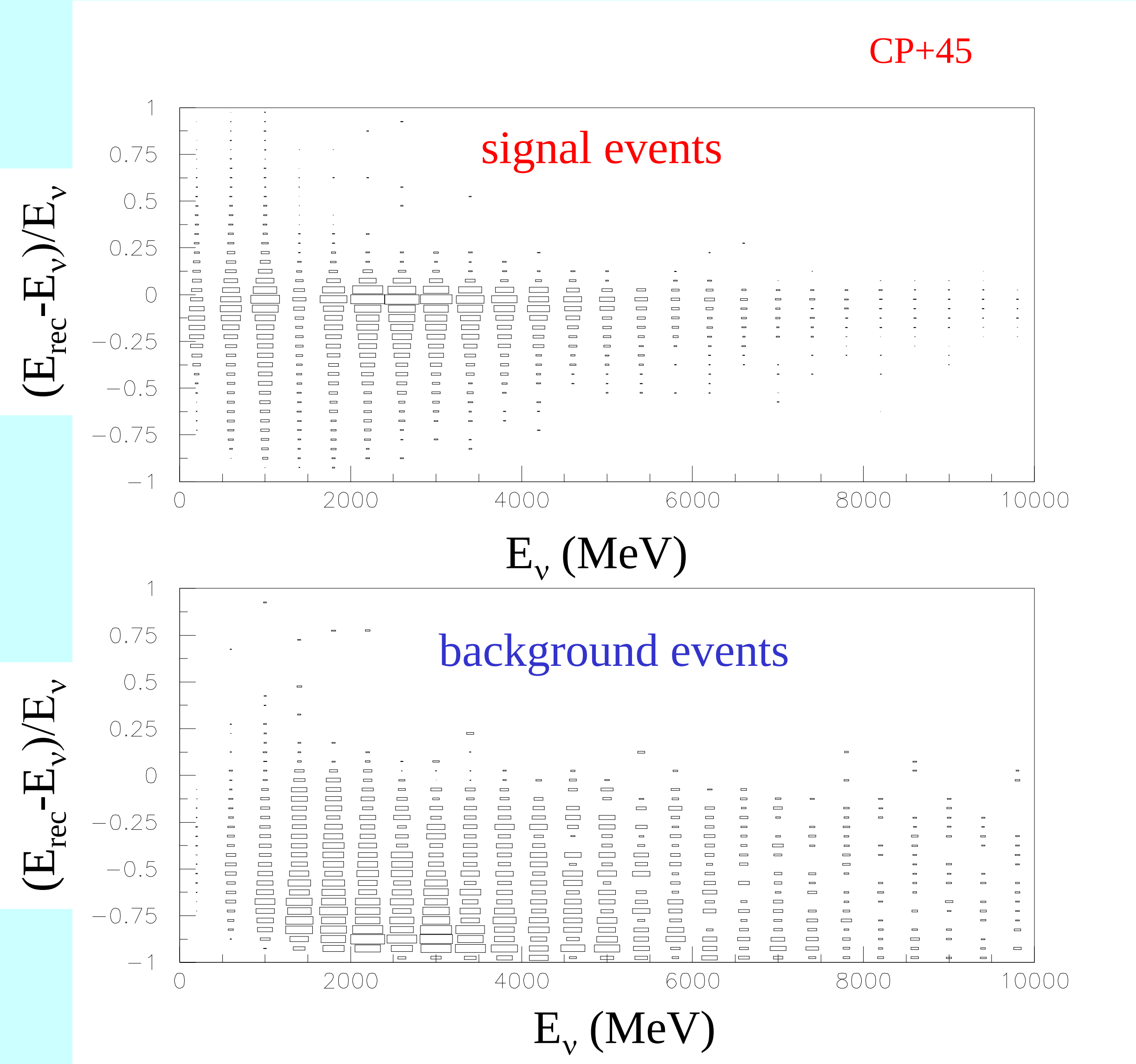
- Breakdown of interaction mode

Interaction mode	$0<E_{rec}<1$ GeV Sig	Bkg π^0	$1<E_{rec}<2$ GeV Sig	Bkg π^0	$2<E_{rec}<3$ GeV Sig	Bkg π^0	3 GeV$<E_{rec}$ Sig	Bkg π^0
CC QE	82%	7%	69%	1%	28%	0%	50%	0%
1 π^0	3%	3%	5%	8%	11%	0%	8%	0%
1 π^{+-}	14%	7%	22%	1%	45%	0%	30%	0%
DIS	1%	0%	3%	1%	15%	18%	13%	0%
NC 1 π^0	0%	39%	0%	68%	0%	23%	0%	25%
1 π^{+-}	0%	29%	0%	3%	0%	0%	0%	0%
DIS	0%	11%	0%	9%	0%	59%	0%	75%
Others	0%	3%	1%	10%	3%	0%	0%	0%

Fermilab-Henderson (1480 km)

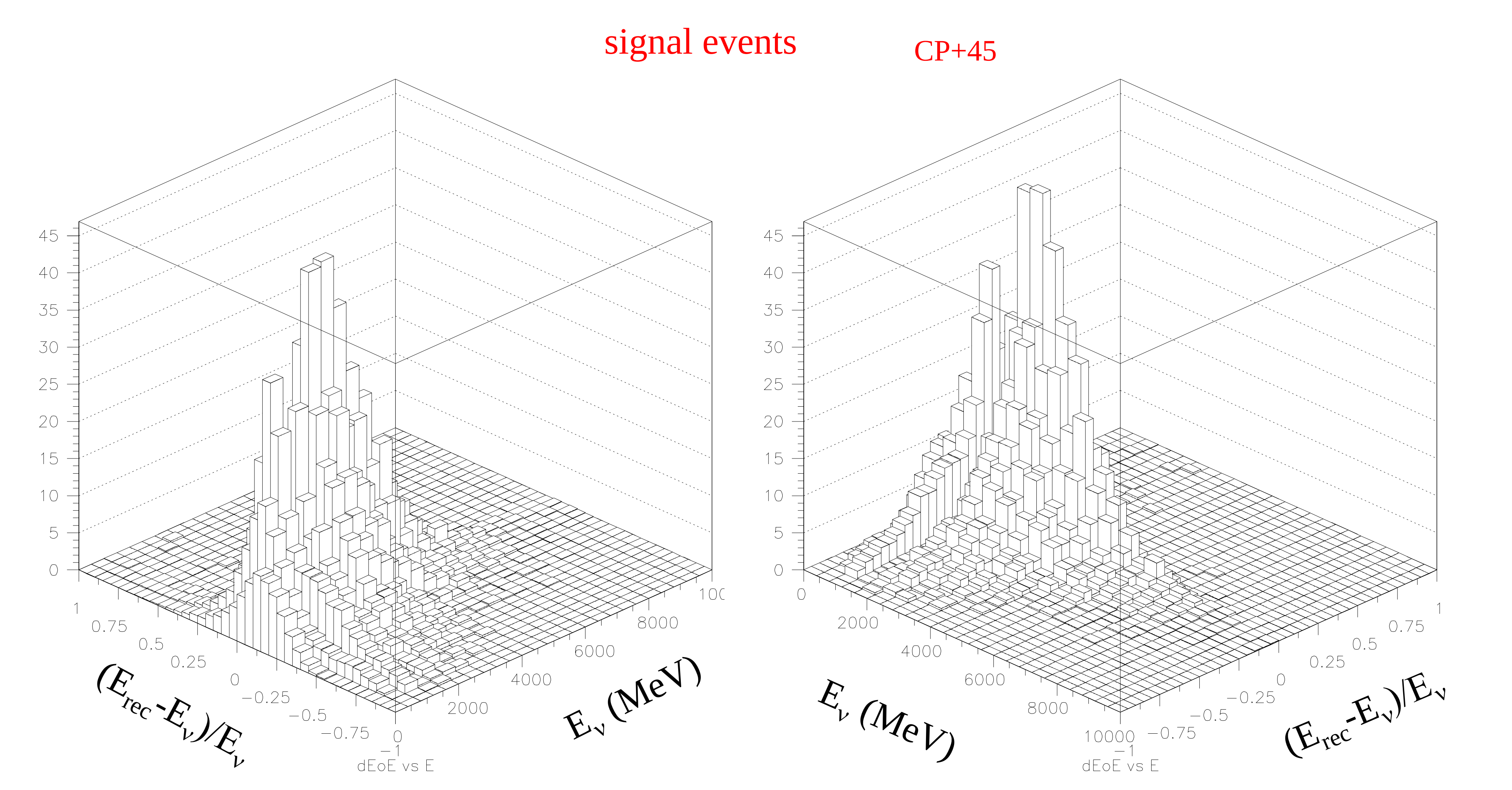
- How good is the neutrino energy measurement?

  - **Neutrino energy reconstruction**



Fermilab-Henderson (1480 km)

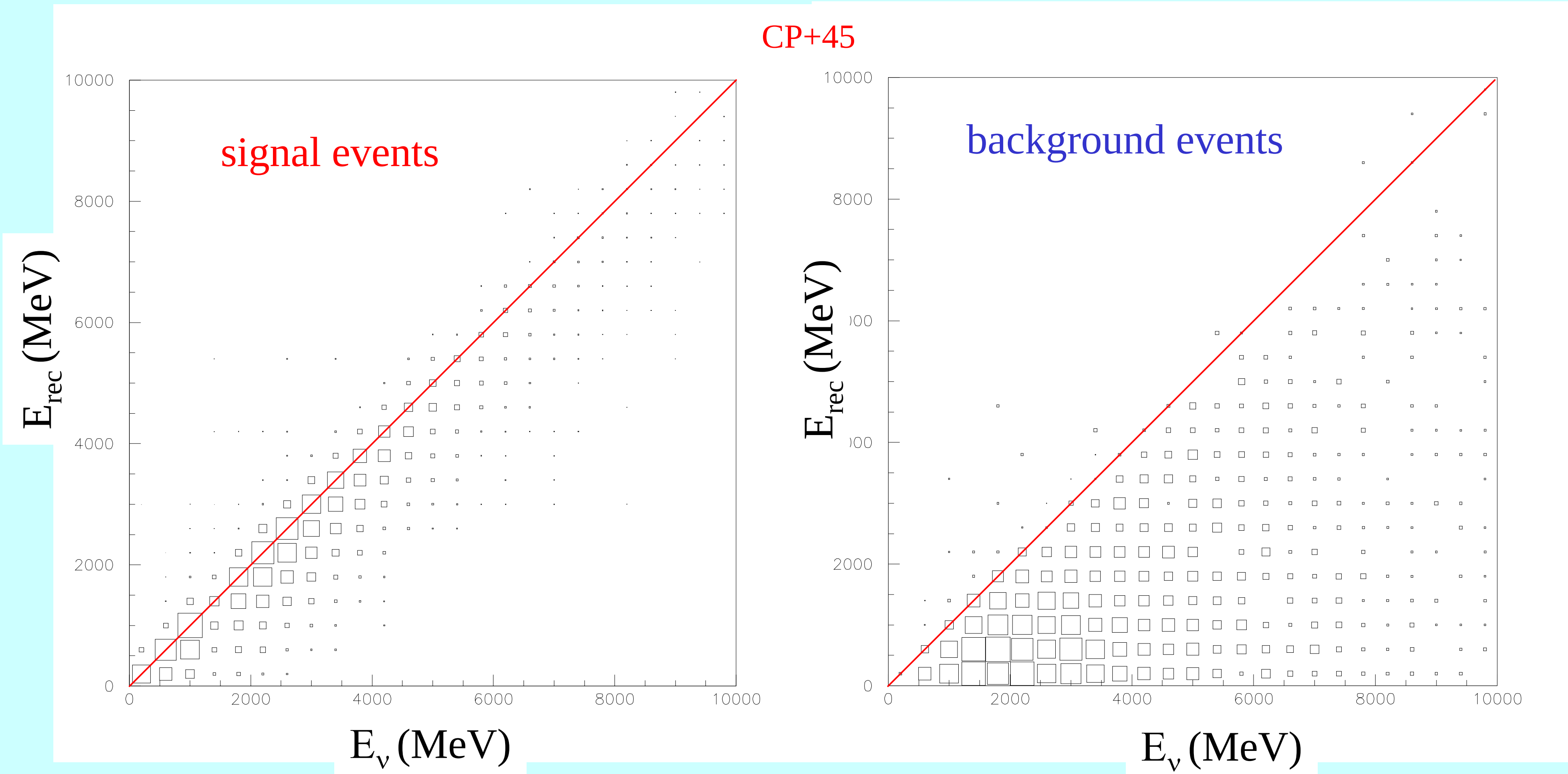
- How good is the neutrino energy measurement?
  - **Neutrino energy reconstruction**



Fermilab-Henderson (1480 km)

- How good is the neutrino energy measurement?

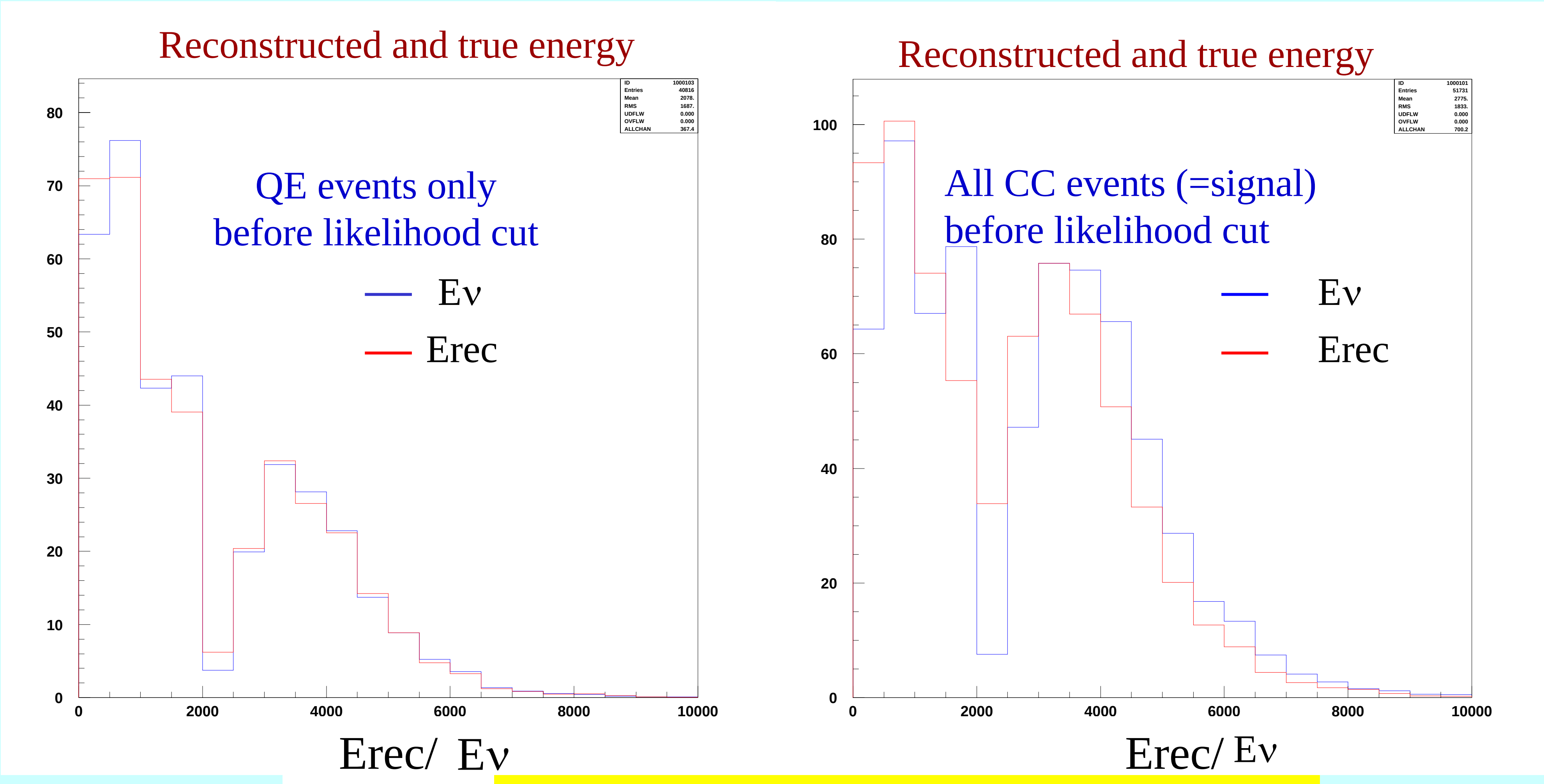
  - **Reconstructed neutrino energy vs. true neutrino energy**



- How well can we measure neutrino energy ?

From now on only single e-like events after initial cuts will be used

Oscillation effect on with CPV+45^{o} at 2,540 km

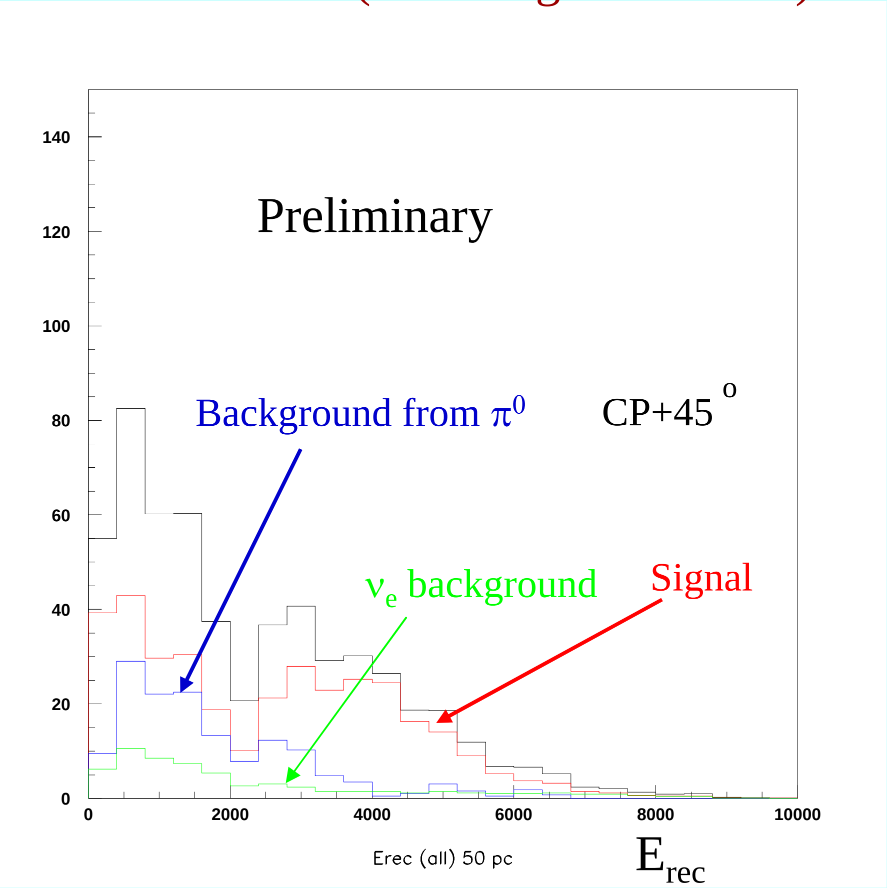


All CC events that survive the initial cuts are signals

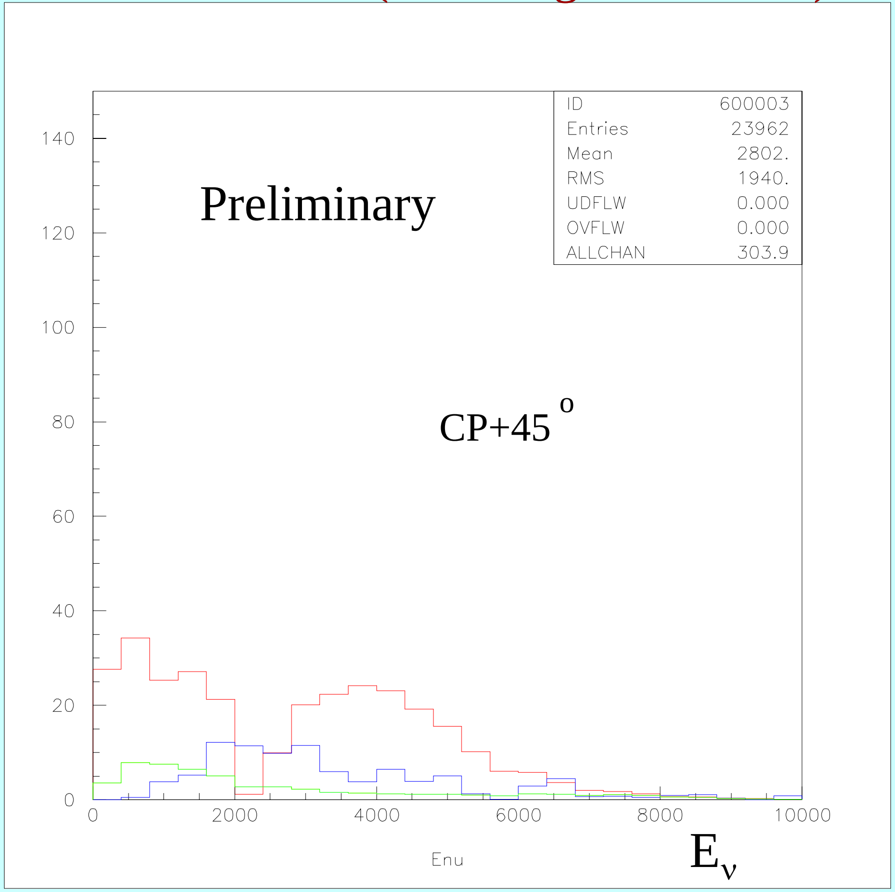
BNL-Homestake (2540 km)

- E_{rec} vs. E_{ν}

Δlikelihood cut (~40% signal retained)

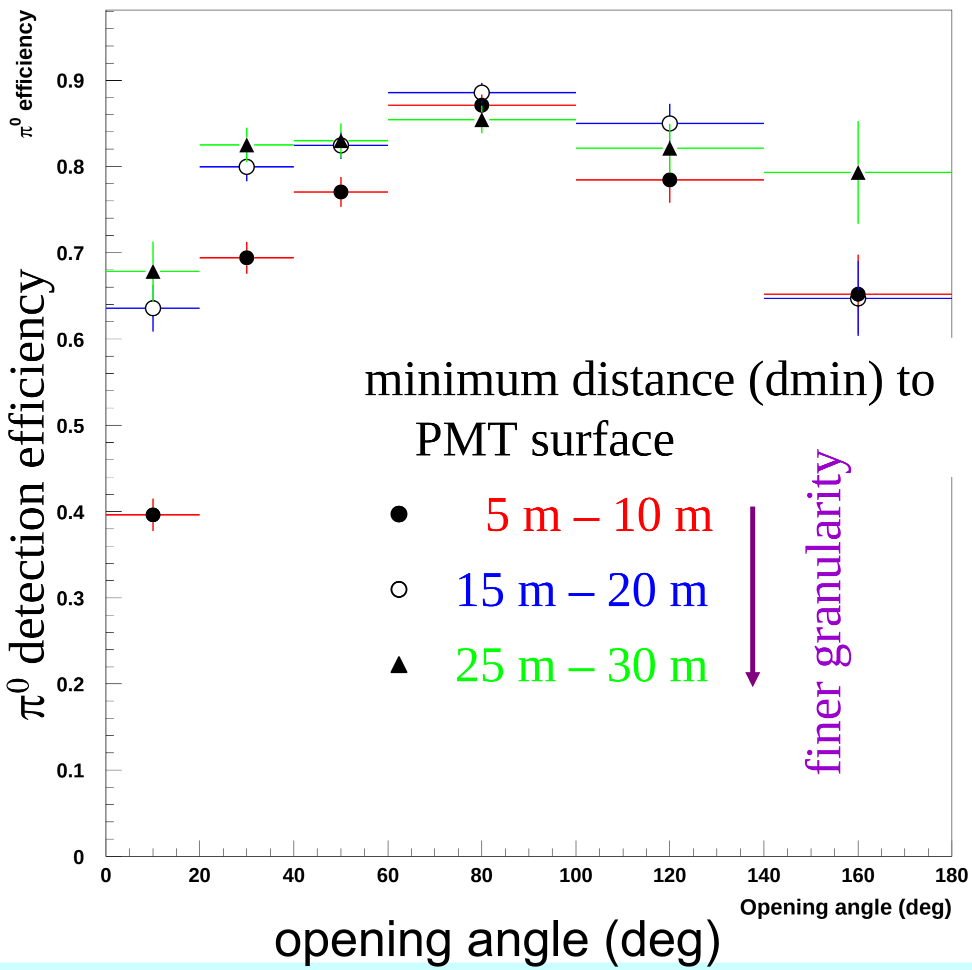


Δlikelihood cut (~40% signal retained)



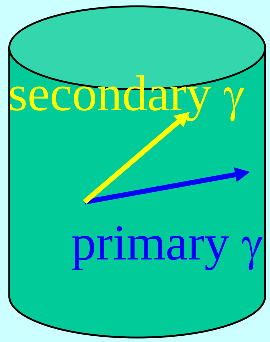
• Granularity and π^0 efficiency for same PMT coverage

Expected improvement with UNO?



Compared with a smaller detector

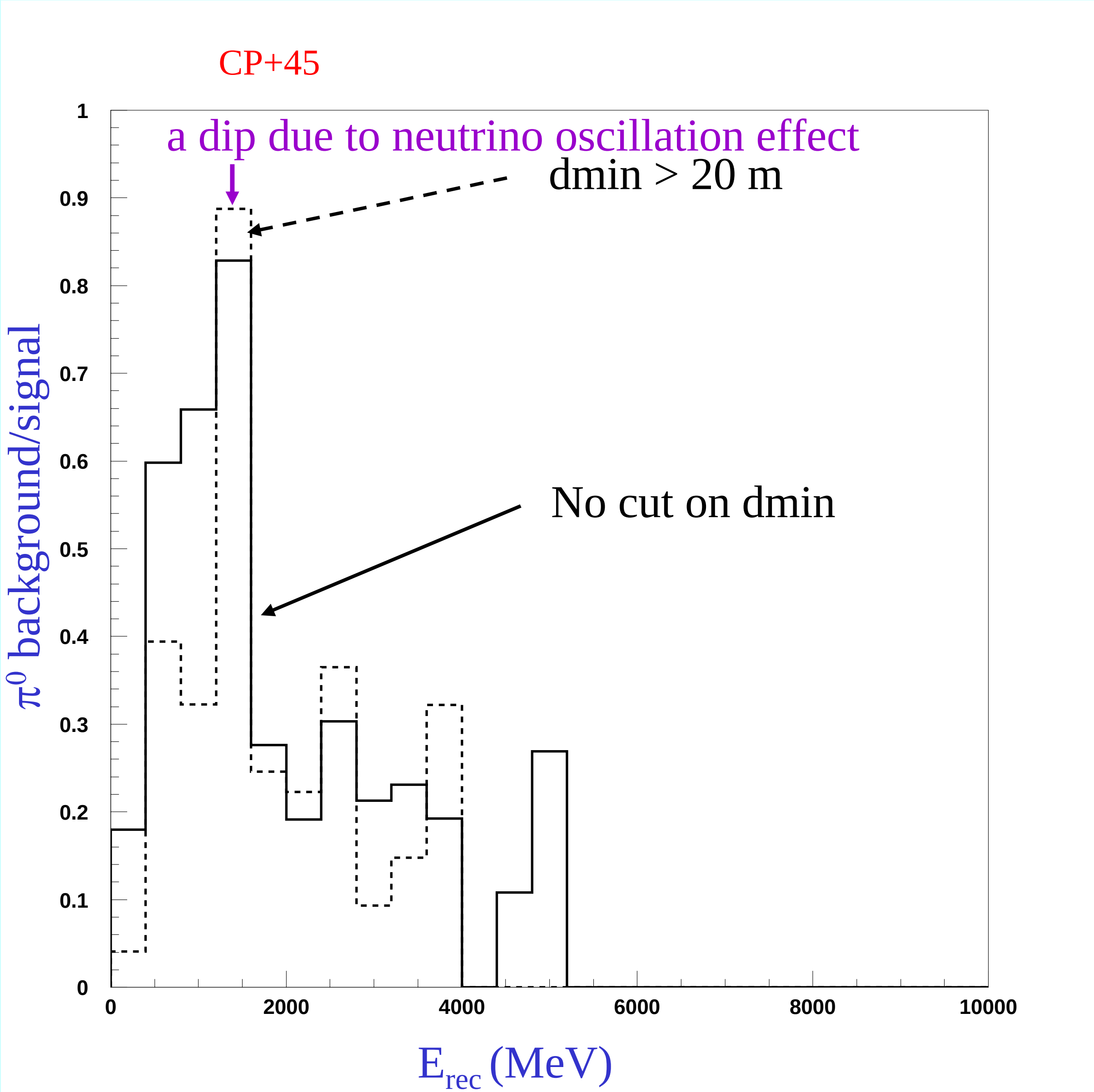
- π^0 efficiency improves when min. distance increases when the opening of two photons from π^0 is smaller than about 40^0.
- For smaller π^0 opening angle finer granularity is needed.
- What PMT coverage needed? 10,20,40% (SK-I and SK-III has 40% coverage) ?



dist>dmin

Fermilab-Henderson (1480 km)

- Effect of granularity on π^0 background/signal



A larger water Cherenkov detector does a better job to distinguish the signal from the π^0 background at the re-constructed energy below 1.2 GeV.

• Conclusions

- Using a realistic MC simulation, the BNL wideband ν_μ beam combined with a UNO type detector was found to DO A GREAT JOB whether the baseline is 2,540 km or 1,480 km.
  - Very exciting news ! But always do proper MC simulations!
- A larger detector such as UNO has an advantage over a smaller detector such as SK (we learned a lesson from 1kt at K2K): Both PMT coverage AND granularity are important
- There is still room to improve S/B ratio beyond the currently available reconstruction software for water Cherenkov detectors.
  - We may need further improvement of algorithm/software, which is quite doable.
  - To access capability of the next generation large water Cherenkov detectors, a new set of software should be developed (frame work done).
- In collaboration with BNL and Fermilab, proper simulations of a next generation water Cherenkov detector, its optimized design with reasonable ν_μ beam will produce fruitful results on exciting physics